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LA-UR -88-748

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TITLE: FLUID DYNAMICAL MODEL OF ULTRARELATIVISTIC HEAVY ION COLLISIONS

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SUBMITTED TO: Proceedings of a "Heavy Ion Meeting," Sun Valley, Idaho [redacted]., February 22-29, 1988.

Fluid Dynamical Model of Ultrarelativistic Heavy Ion Collisions†

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ABSTRACT: The aim of the present paper is to investigate the effects a phase transition to a quark-gluon plasma. During the phase transition a large portion of the initial kinetic energy is invested in the latent heat. At late expansion stages we gain back this energy as random thermal motion and not as directed collective flow. In the framework of a three dimensional relativistic fluid dynamical model the sensitivity of dN_π/dy, and $< p^x/a >$ on the equation of state are pointed out.

Fluid dynamical calculations have been performed for high energy nuclear collisions already [1]. However, all three-dimensional calculations so far have included an equation of state (EOS) without any phase transition whatsoever. The phase transition in baryon-rich matter has been considered only in one - dimensional calculations up to now. Thus a clear prediction of the type of fluid-dynamical flow signal does not really exist so far. All "predictions" are based on essentially one-dimensional calculations. The essence of these predictions is that the transverse flow should decrease in the presence of a phase transition in a given energy region. This is due to the fact that the pressure is strongly decreased by the deconfinement phase transition in the mixed phase region.

In all fluid dynamical calculations the EOS-s is the basic input about the matter properties. The first phenomenological equations of states were constructed [2-5] by using a very simple form for the nuclear equation of state. The energy density E in terms of density n and temperature T was parametized as a sum of the nucleon rest mass, the binding energy, the compressional energy E_{comp}, and the thermal energy described as that of a Boltsmann ideal gas. At high temperatures pion gas should also be taken into account. For the QGP phase in zeroth order of perturbation theory the pressure p in terms of T and bag constant B is given by the MIT bag model Equation of State. Having defined both the Hadronic and QCD plasma equation of state, one can create a complete EOS by a Maxwell construction, containing pure phases and a region where the above two phases coexist.

For our numerical fluid dynamical study we have selected one EOS for which we tabulated the pressure as a function of the baryon density and energy density. The selected equation of state has a first order phase transition, Fig. 1. There are relatively few calculations yet describing the baryon rich matter in the ultrarelativistic energy region [2,3,6-9]. Three dimensional calculations [1] did not consider a phase transition into QCD plasma in the EOS. One - dimensional calculations have yielded some interesting results arising from the phase transition. The threshold to reach the mixed phase lies around $4 - 5 GeV/nucleon$ laboratory beam energy, if we assume complete stopping. Already around $10 - 15 GeV/nucleon$ one might reach the pure QGP phase. Of course transparency and sidewards flow might push these thresholds somewhat higher, but these threshold values are very promising in any case.

During the fluid dynamical calculation in the one fluid model we always calculate the baryon density N, the momentum vector $M^i = T^{0i}$ and the energy density $E = T^{00}$. These quantities are not Lorentz invariant scalars, but they are obtained as one could observe them in the frame of the calculation (which is usually the nucleon-nucleon or the nucleus - nucleus c.m. frame). The baryon density N is actually the 0'th component N^0 of the baryon current four vector N^μ. During the calculation at every timestep we find the local rest frame of every fluid cell and also evaluate the invariant scalar baryon density n and energy density e: $n = U^\mu N_\mu$, $e = U^\mu T_{\mu\nu} U^\nu$. Then by using the EOS we can find the local pressure p, temperature T, etc. In order to account for both the collective fluid-dynamical motion and for the random thermal motion of the nucleons

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† Sun Valley '88

we have to consider the thermal baryon distribution locally in every fluid cell and boost it by the velocity of the cell. The local baryon distribution is not really known, unfortunately, so we have to make simplifying assumptions. We assume that the local baryon momentum distribution is a Jüttner distribution $f(x,p)$. This means that we assume an ideal gas momentum distribution for the baryons. Consequently this approximation is adequate only at the freeze-out stage of the reaction where the interactions among the fragments are weak.

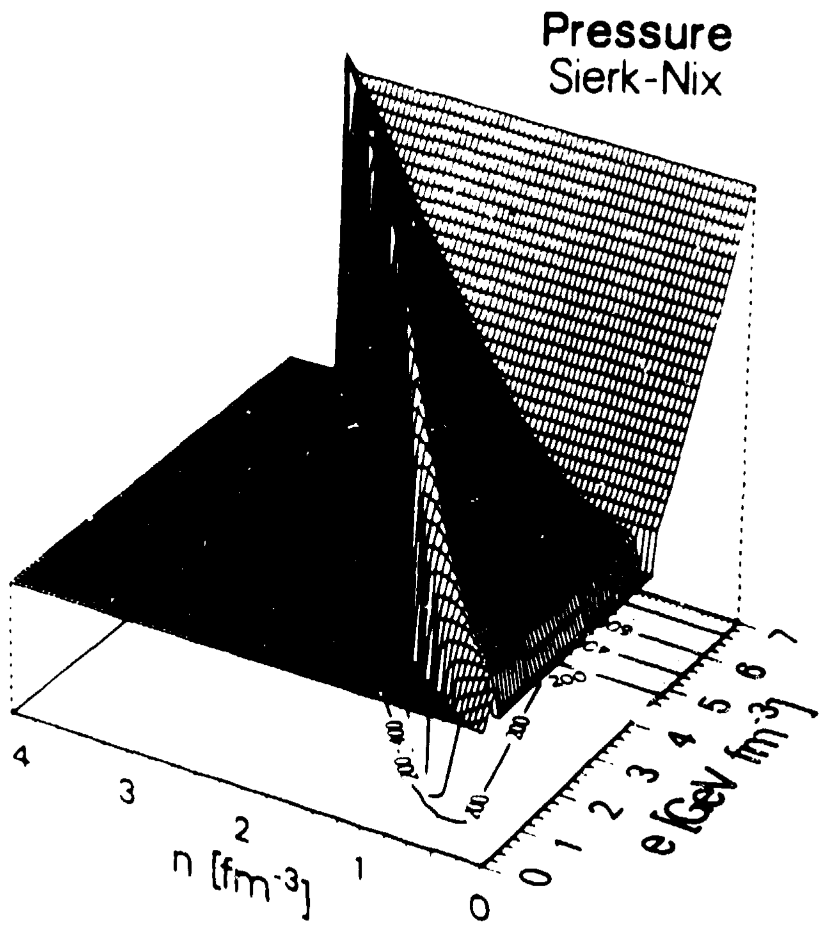

Fig. 1 The Equation of State of the Quark - Gluon Plasma, Hadronic Matter and Mixed phase calculated phenomenologically. The pressure is plotted vertically in MeV/fm^3 units versus the baryon charge density n and the rest energy density e. The Hadronic matter EOS is taken from a parametrisation given by Sierk and Nix. The QGP is given by the MIT-bag model EOS and the mixed phase is calculated from the Gibbs relations.

For qualitative orientation, however, we evaluated the rapidity distribution at intermediate stages of the reaction also following the same method. The total baryon number in a fluid cell is an invariant scalar:

$$N_{cell}^{tot} = \int d^3x\, N^0(x) = \int d^3x \int d^3p\, f(x,p)$$

If the cell four velocity is $U^\mu = \gamma(1, \beta_\parallel, \beta_\perp)$ then $V_{cell} = V_{LR}/\gamma$, $N^0 = n\gamma$, and V_{LR} is the local rest frame (LR) volume of the fluid cell, which is an invariant scalar. We can split up the second integral by observing that $d^3p = dp_\parallel d^2p_\perp = p^0 dy\, d^2p_\perp$. Thus the contribution of a fluid cell to the final baryon charge distribution

$$\frac{dN_{B_{cell}}}{dy} = V_{cell}\gamma\frac{dn}{dy} = V_{cell}\gamma\frac{d}{dy}\int d^3p\,\frac{1}{p^0}p^\mu U_\mu f(x,p)$$

Performing the integral in an appropriate reference frame yields:

$$\frac{dN_{B_{cell}}}{dy} = \frac{V_{cell}\gamma g_N}{(2\pi\hbar)^3}\exp(\frac{\mu}{T})\,2\pi T m_\perp^2\,[1 + \frac{2}{(h'm_\perp)} + \frac{2}{(h'm_\perp)^2}]\exp(-h'm_\perp).$$

where $h' = \gamma'[ch(y) - \beta_\parallel sh(y)]/T$, and $\gamma' = 1/\sqrt{1-\beta_\parallel^2}$. Integrating this over the rapidity y yields the total baryon number in the fluid cell. The final rapidity distribution of the baryon charge is then obtained by summing up the contributions from all the fluid cells:

$$\frac{dN_B}{dy} = \sum_{cell}\frac{dN_{B_{cell}}}{dy}$$

This distribution is that of the net baryon charge only. Baryon pairs created during the collision are not included. The calculated dN_B/dy functions for a symmetric $Ca + Ca$ reaction at $14.5 GeV/nucleon$ beam energy are shown in Fig. 2ab for Hadronic and QGP EOS-s.

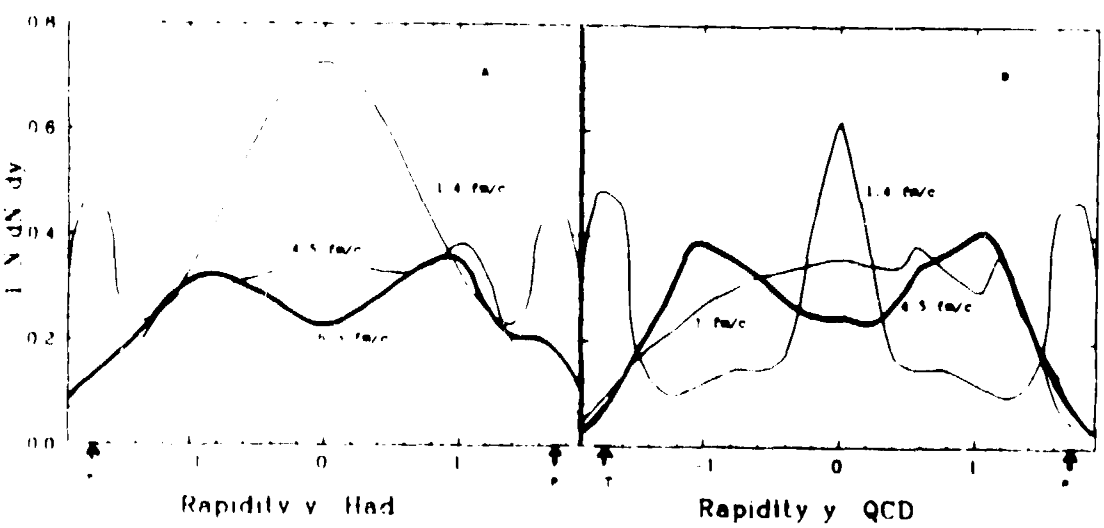

Fig. 2 The net baryon charge rapidity distribution $1/N\, dN_B/dy$ from a preliminary calculation in the relativistic 3 - dimensional one - fluid dynamical model using the PIC method [1b]. The reaction is $Ca + Ca$, $E_{Lab} = 14.5 GeV/nucleon$, $b = 0.3(R_p + R + t)$. The three lines belong to different times measured from the impact. Two different EOS-s were used without (a) and with (b) a phase transition into QGP

The interesting feature that in both cases there is a double peak structure similar to the one one would expect from partial transparency.

The existence of the collective sidewards flow was predicted long time ago as the best signal of the compression of nuclear matter in supersonic shock-waves [10-12]. We can evaluate the transverse flow $\langle p^x/a\rangle$ in relativistic fluid dynamics. Since we know the reaction plane exactly the majority of the complications is nonexistent in a theoretical calculation. Under the same assumptions that were used above we can calculate the contribution of a fluid cell to the transverse momentum projected to the reaction plane (x,z) $P^x_{cell} = V_{cell}\int d^3p\, p^x f(x,p)$. In the same way as for the baryon distribution then:

$$\frac{dP^x_{cell}}{dy} = V_{cell}\int d^2p_\perp p^0 p^x f(x,p)$$

This quantity is not an invariant scalar therefore we are not allowed to evaluate it in an arbitrary frame. After a straightforward calculation we can arrive to the result which can be expanded into a power series. Then the resulting sum can be integrated over $p_\perp$, yielding the final result:

$$\frac{dP^{*}_{cell}}{dy} = 2\pi\, ch(y) m^2 \sqrt{\frac{2}{\pi}}\, A V_{cell}\, cos(\phi_R) \sum_{k=0}^{\infty} \frac{g^{2k+1}}{2^k k!} \left(\frac{m}{h}\right)^{k+\frac{3}{2}} \left[K_{k+\frac{5}{2}}(hm) + \frac{2(k+2)}{hm} K_{k+\frac{3}{2}}(hm)\right]$$

where $h = \gamma[ch(y) - \beta_{\|} sh(y)]/T$, ϕ_R is the azimuth angle of the fluid cell measured from the reaction plane, the constant A is given in terms of the baryon density and cell temperature as $A = n/[4\pi m^2 K_2(m/T)]$, and $g = \gamma\beta_\perp/T$. The average transverse momentum per nucleon at a given rapidity y is given by

$$< p^{*}/a > = \frac{\sum_{cell} dP^{*}_{cell}/dy}{\sum_{cell} dN_{Bcell}/dy}.$$

In the practical evaluation of $< p^{*}/a >$ we increased the temperature of the cells which were colder than $15 MeV$, to $15 MeV$. This partly compensates for the neglected fluctuations and the underestimated zero and low temperature momentum spread. The transverse momentum as measured by the maximum of the $< p^{*}/a >$ distribution, decreases with increasing energy. This tendency was clearly observable already in the lower energy data [13]. In Fig. 3ab the calculated $< p^{*}/a >$ rapidity distribution are shown with and without quark-gluon phase transition under the same conditions as in Fig. 2. We see that the transverse momentum increases with time. In the case of phase transition it is smaller than in the case without phase transition by about a factor of 2. This might serve as signature of QGP phase transition. Partial transparency, however, leads to a decrease of the $< p^{*}/a >$ also.

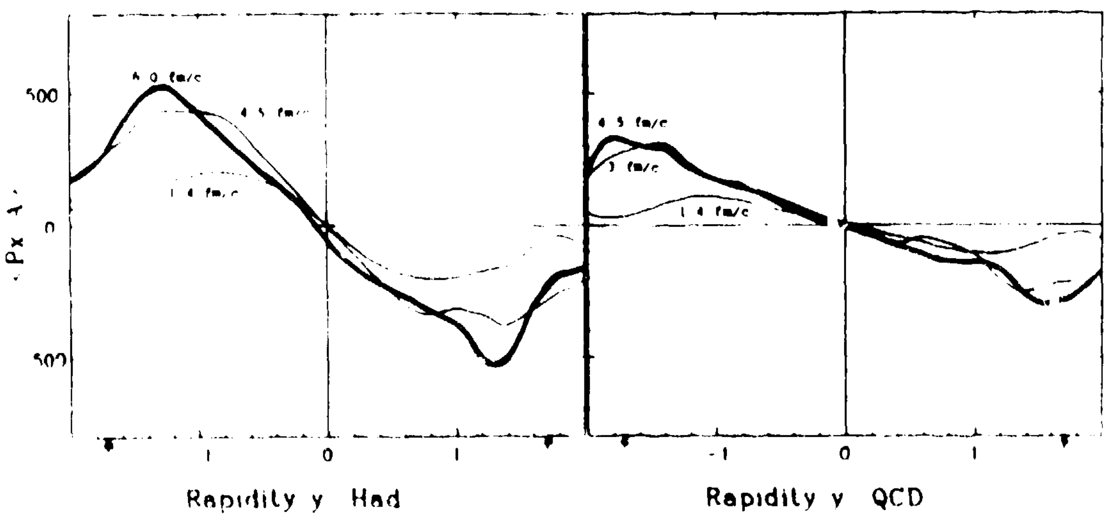

Fig. 3 The net baryon charge transverse momentum distribution $< p^{*}/a >$ from a preliminary calculation for the same reaction as in Fig. 2. The three lines belong to different times measured from the impact. Two different EOS-s were used without (a) and with (b) a phase transition into QGP. The phase transition leads to an essential decrease of the transverse momentum projected into the reaction plane.

We also calculate the average transverse momentum $< p_\perp/a >$ which is the magnitude of tranvserse projection of momentum. Similar to the case of $< p^{*}/a >$, we have

$$\frac{dP_{\perp cell}}{dy} = V_{cell} \int d^2 p_\perp\, p^0 p_\perp\, f(x,p) =$$

$$= 2\pi\, ch(y) A V_{cell} \sum_{k=0}^{\infty} \frac{g^{2k}}{(2k)!!^2} (2k+3)!!\left(\frac{m}{h}\right)^{k+2} \left[K_{k+2}(hm) + \frac{hm}{2k+3} K_{k+1}(hm)\right]$$

Thus the average $p_\perp$ per baryon:

$$< p_{\perp}/a > = \frac{\sum_{cell} dP_{\perp cell}/dy}{\sum_{cell} dN_{Bcell}/dy}$$

Summary: In the stopping energy region which is expected to include the phase transition threshold one can make use of a phenomenological EOS if the matter is not too far from local thermal equilibrium. The one-fluid dynamical model as one extreme, assuming local thermalisation, yields strong changes in the flow pattern. We expect a strong decrease in the projected net baryon transverse momentum $< p^x/a >$ due to the phase transition. The rapidity distribution of the baryon charge shows two peaks according to our calculations. This is very similar to the behaviour one would expect from strong transparency. This indicates that caution is necessary when we draw conclusions about the stopping of nuclear matter in $A+A$ collisions.

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